BOTTOM AND SURFACE PROXIMITY EFFECTS
ON THE ADDED MASS OF RANKINE OVOIDS

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THESIS

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on the Added Mass of Rankine Ovoids

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by

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ABSTRACT

The free-surface and bottom-proximity effects on the added mass of Rankine ovoids of various length-to-diameter ratios were experimentally investigated by vertically oscillating the ovoids normal to their major axis.

The results have shown that the bottom-proximity increases the added mass and the free-surface proximity decreases it. Furthermore, the added mass increases with increasing length-to-diameter ratio, i.e., for more cylinder-like ovoids, and approaches that predicted analytically for an infinitely long cylinder. Finally, an appropriate analysis based on the strip-method and the cylinder results has shown that the bottom-proximity effect on the added mass of Rankine ovoids may be predicted with sufficient accuracy. The prediction of the surface-proximity effect requires more refined methods.

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NOMENCLATURE

Symbol	Description
a	- distance to source or sink from origin of coordinate system
C	- added mass coefficient
U	- free stream velocity, uniform flow
D	- diameter of Rankine ovoid at mid-length
L	- length of Rankine ovoid
h	- distance from centerline of Rankine ovoid to rigid bottom
b	- distance from centerline of Rankine ovoid to free surface
TB#_	- test body number
W	- weight of test body
W_a	- added weight
W_d	- displaced weight
W_t	- total weight
τ	- period of oscillation
f	- frequency of oscillation
δ	- L/D
η	- b/D
ξ	- h/D
ϕ	- potential function
ψ	- stream function
ω	- radius of Rankine ovoid
Q	- source or sink strength
S.G.	- specific gravity

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The author wishes to thank Professor T. Sarpkaya for suggesting the research topic and for his guidance throughout the investigation, from its inception to the completion of the final manuscript.

I. INTRODUCTION

One of the most important problems in the design of bodies moving through a fluid is the evaluation of the inertial resistance of the fluid when the body is subjected to accelerations or decelerations. This inertial resistance affecting body motion is usually described in terms of an apparent increase in the mass (added mass) of the body. The fundamental concepts of the added mass and the historical developments are amply described in most hydrodynamics books (e.g. Robertson [1]).

The added mass and the added-mass-moment of inertia are, in general, functions of the shape of the body, the direction of body motion, the existing state of fluid motion (e.g. motion from rest, motion from one steady state to another, deceleration to rest from a steady state), the physical properties of the fluid (i.e., density, viscosity, and compressibility), and the proximity of other bodies, rigid boundaries, or a free surface (fluid interface). Although in theory the added-mass and added-mass-moment of inertia coefficients can be computed for any body shape and flow combination, the actual solution of the problem often proves mathematically intractable. The greatest difficulties are encountered in determining the added mass for bodies accelerating from a state of steady motion and for bodies which are

not deeply submerged (bodies near a free surface) or bodies which are too deeply submerged (near the ocean bottom).

Considerable analytical and experimental work has been done on the determination of the added mass of bodies of relatively simple shape immersed in a fluid medium of infinite extent [1]. Good agreement has been obtained between analytical and experimental results where the body or the fluid is accelerated from rest. The understanding and evaluation of the added mass for bodies accelerating from a steady state (with separated fluid motion) to another state are still at a formative stage and most of the current design is based on empirical formulas (e.g., Morrison, _et al_ [2]).

Concerning the effects of the free-surface or bottom proximity on the added-mass coefficient, relatively few analytical and experimental studies have been carried out (e.g., Waugh and Ellis [3], Sarpkaya [4], Garrison [5], Garrison and Berklite [6]). The analytical methods are based on the image method, distributed sources, finite element technique, etc. Experimental methods are based mostly on the determination of the change of frequency of the body oscillation in air and water. Analytical methods are particularly convenient when the effect of damping is ignored and the added-mass coefficient is rendered independent of the frequency of oscillation of the body.

Rankine ovals and ovoids constitute a large family of plane and axisymmetric bodies of special interest to hydrodynamicists and naval engineers. The added-mass coefficients for these bodies may easily be calculated since only simple singularities are involved in their definition in fluids of infinite extent. When these bodies are in the proximity of a free surface and/or rigid boundary, however, the determination of the added mass is considerably complicated by the need to introduce additional isolated or distributed singularities. The problem is further complicated when the free surface can be taken neither as a rigid surface nor as a surface of zero potential [1]. Under these circumstances, it may be preferable to resort to simple experimental techniques to determine the effect of the surface or bottom proximity on the added mass of bodies of arbitrary shape.

The present work consists of the experimental determination of the added mass of Rankine ovoids of various length-to-diameter ratios positioned at various distances from the free surface or rigid bottom. The bodies were vibrated along a line normal both to the free surface of the fluid and the major axis of the body. The added-mass coefficients were determined in terms of the appropriate governing parameters. The results are in conformity with the previous findings for other types of bodies in that the proximity of the free surface decreases the added mass, whereas the proximity of the rigid bottom increases it [3].

II. DEFINITION OF THE BODY SHAPE AND THE GOVERNING PARAMETERS

Rankine ovoids are the type of axisymmetric bodies obtained by placing a three-dimensional (point) source and sink, each of strength Q, at equal distances "a" from the origin along a line parallel to a uniform flow. Potential and stream functions are written in terms of the bipolar coordinate system shown in Fig. 1 as:

$$\begin{aligned} \phi &= -Q/4\pi r_1 + Q/4\pi r_2 + Ux \\ \psi &= -Q\cos\theta_1/4\pi + Q\cos\theta_2/4\pi + \frac{U\omega^2}{2} \end{aligned} \tag{1}$$

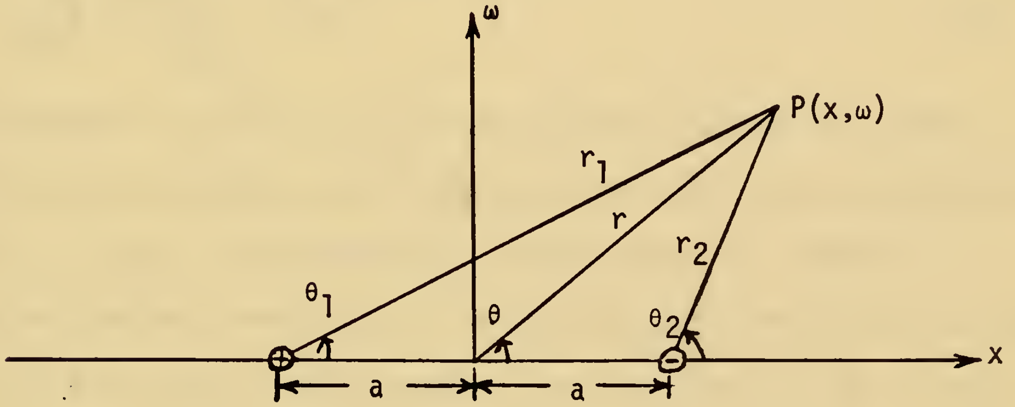


Fig. 1. DEFINITION OF A RANKINE OVOID

The equation of the body contour is obtained by equating the stream function to zero,

$$\omega^2 = \frac{Q}{2\pi U} (\cos\theta_1 - \cos\theta_2) \tag{2}$$

In terms of the parameter $m = \sqrt{Q/2\pi U a^2}$ one has,

$$\frac{\omega^2}{a^2} = m^2 (\cos\theta_1 - \cos\theta_2)$$

or, $$\frac{\omega^2}{a^2} = m^2 \left[\frac{x+a}{\sqrt{\omega^2+(x+a)^2}} - \frac{x-a}{\sqrt{\omega^2+(x-a)^2}} \right] \qquad (3)$$

Apparently, the absolute size of the body is controlled by the source-sink distance "2a", whereas the length-to-diameter ratio is determined by the parameter m. Since a stagnation point exists at $x=\pm L/_2$ taking the derivative of the potential along the x-axis and equating it to zero, one has,

$$^{L}/_{2a} \Big/ \left[\frac{L^2}{4a^2} - 1\right]^2 = \frac{1}{2m^2} \qquad (4)$$

The diameter at x=0 is obtained from Eq. (3) as,

$$\frac{D^2}{4a^2} \sqrt{1+\frac{D^2}{4a^2}} = 2m^2 \qquad (5)$$

Since neither L/2 nor D/2 can be simply solved for, the relationship between m and L/D must be evaluated numerically. Results of such calculations are presented in Table I.

As discussed previously, the added-mass coefficient depends upon the body shape, body motion, properties of the fluid medium, and the proximity of either a free surface or rigid boundary. In this work, the effects of the body shape and the proximity of the free surface or rigid bottom were considered. For the Rankine ovoid, body shape is characterized by the length-to-diameter ratio. The free-surface or the bottom-proximity effect may be expressed in terms of the ratios b/D and h/D (see Fig. 2). Thus, one has

$$C = \frac{\text{added mass}}{\text{displaced mass}} = f(L/D, b/D, h/D) \qquad (6)$$

provided that the viscous and compressibility effects are ignored. Defining $\delta=L/D$, $\eta=b/D$, and $\xi=h/D$, Eq. (6) may be written as

$$C = f(\delta,\eta,\xi) \tag{7}$$

If we consider the effects of the free-surface and bottom proximity independently, by taking $h/D=\infty$ and $b/D=\infty$ respectively, then we have

$$C = f_1(\delta,\eta), \text{ (free-surface proximity effect)} \tag{8a}$$

$$C = f_2(\delta,\xi), \text{ (bottom proximity effect)} \tag{8b}$$

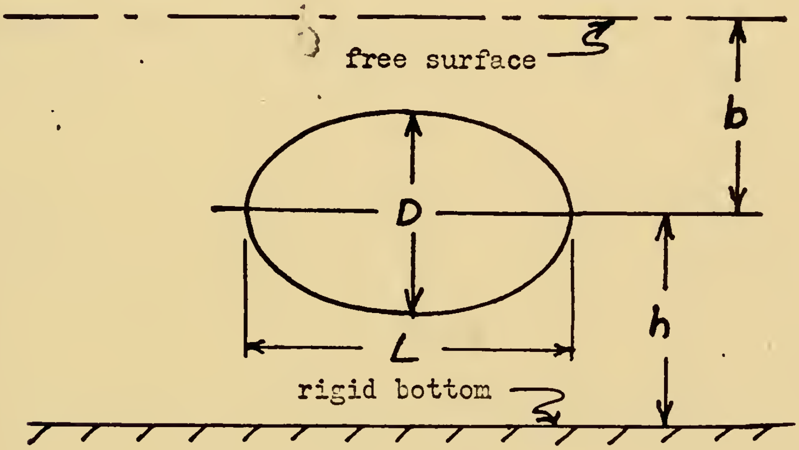


Fig. 2. DEFINITION OF THE BASIC PARAMETERS

It is the experimental determination of the functional relationships represented by Eqs. (8a) and (8b) that constitutes the essence of this work.

As cited earlier, the viscous and compressibility effects were ignored. The effect of compressibility may be neglected when $2\pi fD/c<<1$, where c is the speed of sound in the fluid medium [7]. In fact, taking c=4700 ft/sec, and D=2 inches (the largest value used in this work), one finds that f must be considerably smaller than 4490 cps. As to the effect of

viscosity, an analysis of the forces acting on bodies oscillating rectilinearly in a viscous fluid about a mean position reveals that one part of the force results from the added mass and is in phase with the oscillation. The second part of the force, which opposes the body movement, is out of phase with the acceleration and is thus a damping force producing a decay in oscillation. The analytical results also show that for small amplitudes of oscillation (up to about D/10), the viscosity effects on added mass are quite negligible [7].

TABLE I

RANKINE OVOID PARAMETERS

m^2	L/a	D/a	L/D	C (for $\eta=\xi=\infty$)**	Weight (dry) (gms.)	Weight (sub-merged) (gms.)	Weight of water displ. (gms.)	S.G.	Material	Remarks
0.0	- 2.0	0.00	∞							
0.010	2.144	0.281	7.65	0.915	99.0	15.7	83.3	1.188	plexi-glass	TB # 1
0.0146	2.170	0.340	6.4	0.892	397.9	259.0	138.9	2.862	aluminum	TB # 2
0.0216	2.210	0.415	5.33	0.885	544.0	353.9	190.1	2.862	aluminum	TB # 3
0.0424	2.284	0.572	4.00	0.861	371.8	58.9	312.9	1.188	plexi-glass	TB # 4
0.100	2.199	0.858	3.48	0.821						
0.40	3.11	1.063	2.92	0.772						
1.00	3.60	2.478	1.45	0.665						
∞	-	-	1.00							
					186.8	29.6	157.2	1.188	plexi-glass	cylinder*

*Twelve inches long, with flanged ends. See Fig. 4.

**Unpublished analytical results obtained by Prof. T. Sarpkaya.

III. EXPERIMENTAL EQUIPMENT AND PROCEDURE

The experimental equipment consisted of a four-feet square plexiglass tank with an adjustable false bottom, a pair of parallel cantilever beams, a vibration triggering device, a bridge amplifier meter, and a Monsanto programmable counter timer.

Important considerations in the setting up of the apparatus were the avoidance of the boundary-layer separation and extraneous disturbances, adjustability of the position of the test body relative to the free surface or solid bottom, and the adoption of a suitable and repeatable calibration procedure.

The test bodies (Fig. 4) were made of plexiglass or aluminum and attached to the cantilever beams by two arms (Fig. 5). An ideal solution to this aspect of the instrumentation would have been the use of "action at a distance" whereby the body would be vibrated in the fluid without any material involvement. Such a method was not explored primarily because of the inordinate amount of instrumentation required.

The detrimental effect of the use of two arms to attach the test body to the cantilever beams was reduced by using two thin-walled tubes rather than solid rods. Significant reduction in weight and sufficient rigidity were realized in this manner. An experimental comparison of the effect of the arms (without the body) in air and water was performed. The

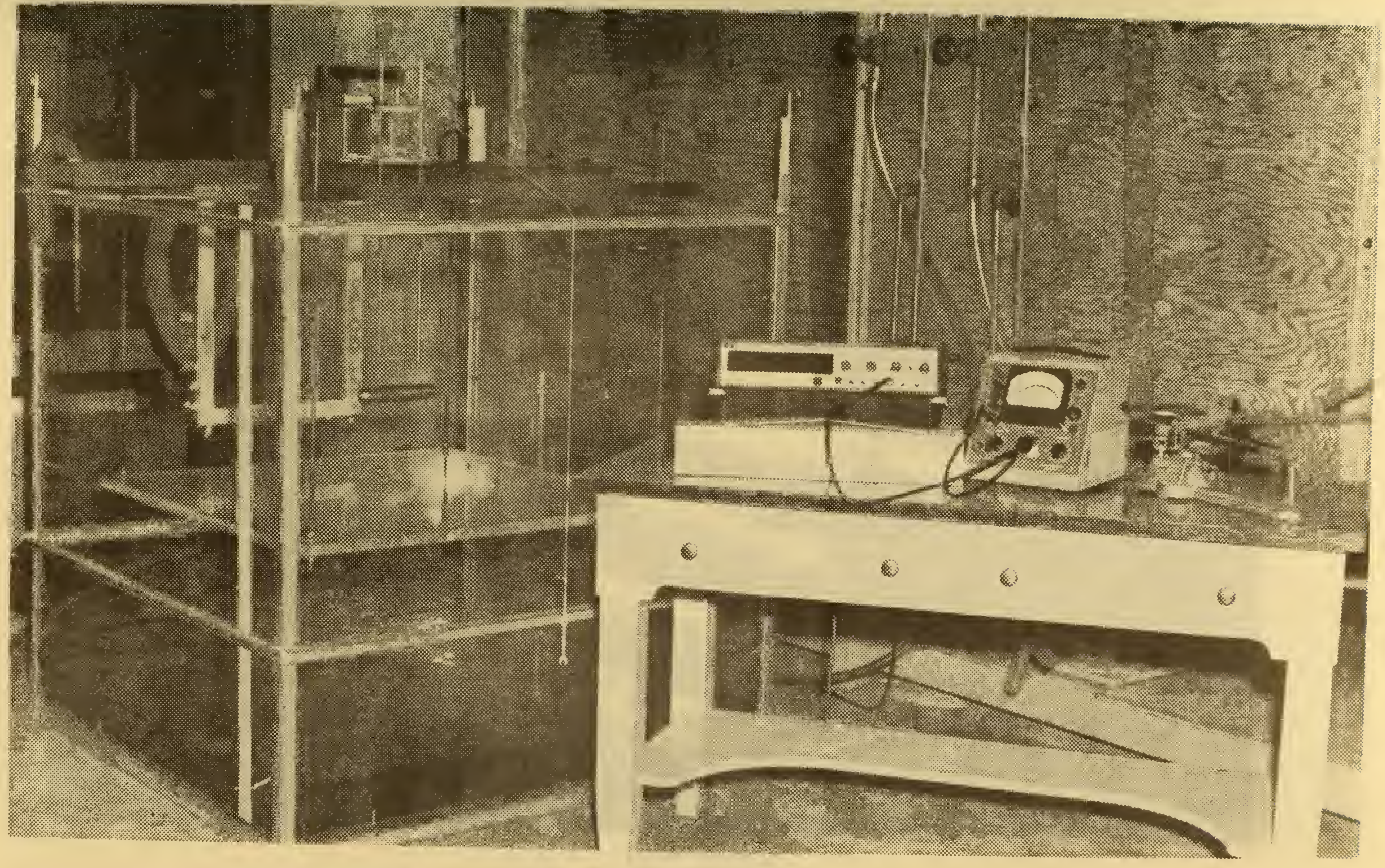


Fig. 3. OVERALL VIEW OF THE EXPERIMENTAL EQUIPMENT

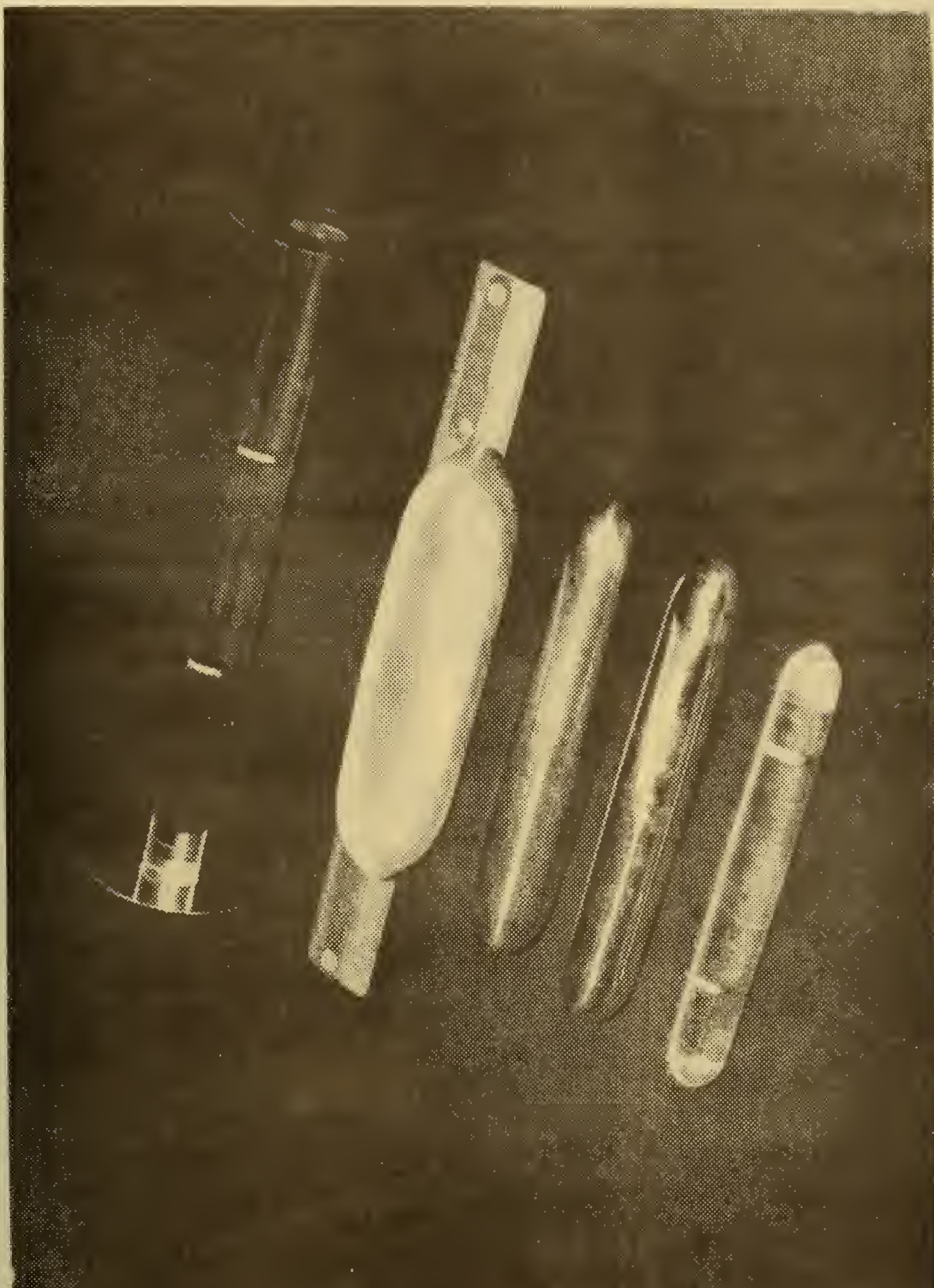


Fig 4. TEST BODIES

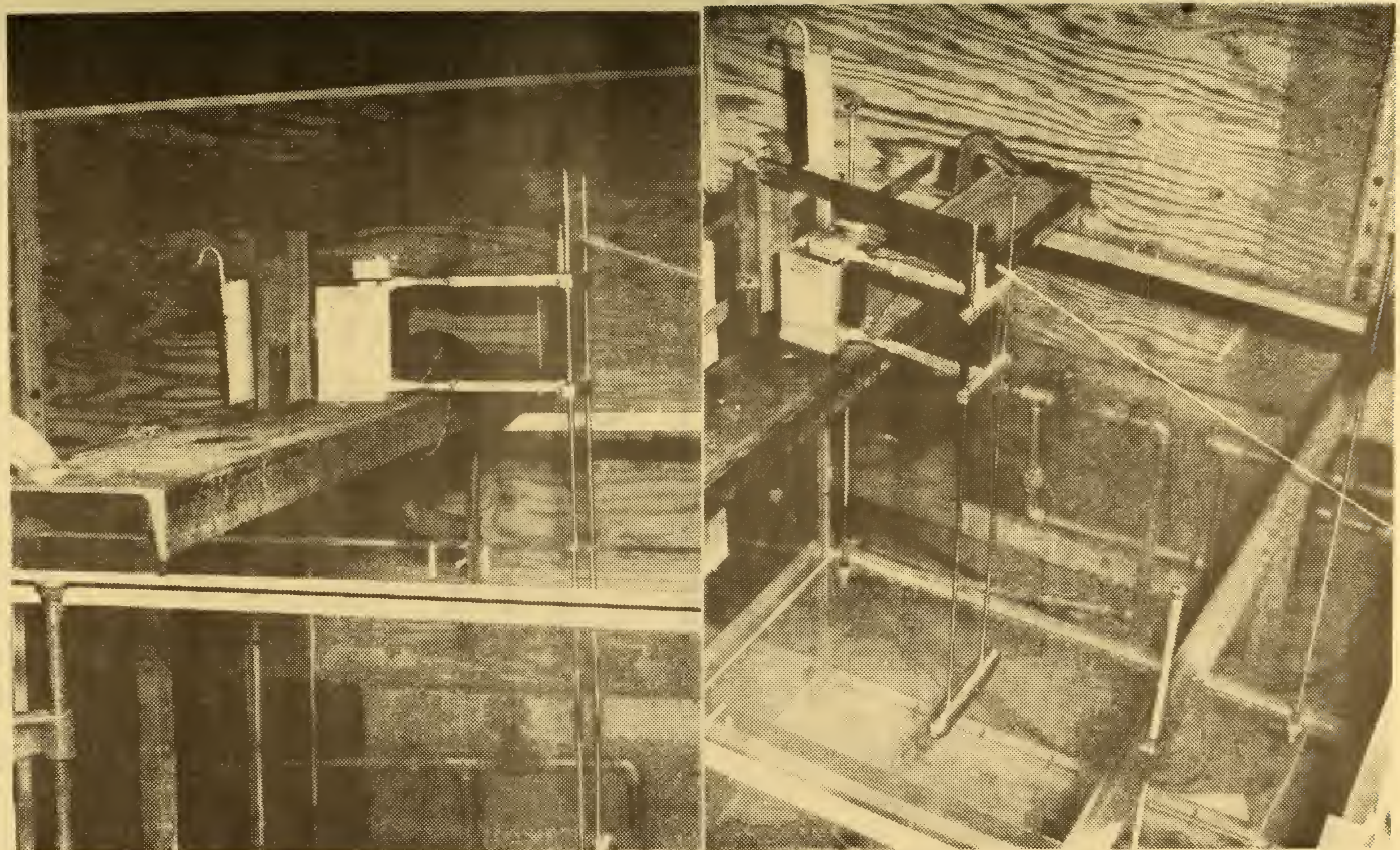


Fig. 5. DETAIL VIEWS OF THE VIBRATION SYSTEM

results shown in Table II indicate that the axial frequency of the vibration of the arms is little affected by immersion in water.

TABLE II

FREQUENCY COMPARISON FOR EMPTY ARMS IN AIR AND IN WATER

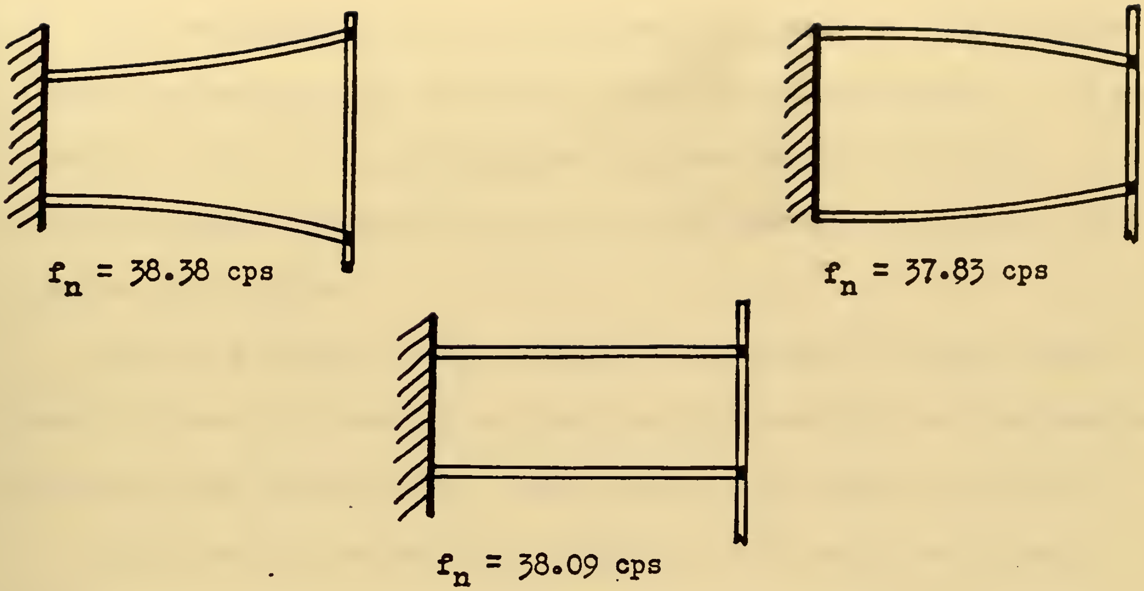
Depth of arms* submerged (inches)	Frequency^{2}** in air $(cps)^2$	Frequency^{2}** in water $(cps)^2$	Ratio (col. 2/col. 3)
5	1560	1555	1.0047
10	1580	1590	0.994
15	1440	1452	0.993
20	1508	1524	0.990
30	1467	1469	0.999

*Length of arms below cantilever beams are equal for air and water

**Average of ten readings

Possible buoyant force effects due to the displacement of water by the arms was considered, and found to have an effect of 0.09% on frequency squared readings. This experiment was performed using the fourth test body at a depth of ten inches and by comparing the data with and without the added weight equal to the displaced water.

Initially it was intended that the variation of the free-surface or bottom proximity would be accomplished by changing the length of the supporting tubes to the test body. However, it was found that the preloading of the cantilever beams resulted in the non-reproducibility of the data. This preloading is illustrated in Fig. 6 (beam deflections exaggerated).



Fi. 6. PRELOADING EFFECTS

This difficulty was overcome by installing a stiffener bar (Fig. 5) with the beams unloaded and subsequently varying the free surface or bottom proximity by changing the water level or adjusting the elevation of the false bottom.

A vibration triggering device was employed to insure consistent initial deflections and to eliminate the human element. It was designed to be adjustable in length so that the variation of the natural deflection of the beams due to the differing weights of the test bodies could be compensated for. The triggering device was adjusted to provide an initial deflection of 1/16 inch for all test bodies, thereby meeting the criteria previously discussed concerning the effect of viscosity, i.e., deflection <D/10.

The programmable counter-timer was used in the period-averaging mode, with readings taken in milliseconds. It was "zeroed" prior to each triggering, whereas the bridge amplifier was "zeroed" prior to each set of ten runs for a single data point.

The test bodies were weighed in air and in water on a beam balance to determine their actual weight and the weight of the water displaced. The results are shown in Table I.

Calibration curves were obtained for each test body, utilizing clamped-on surcharges of known weight. Care was exercised to distribute the weights symmetrically on the test body. The data were plotted with period squared as abscissa and known total weight as the ordinate in view of their projected use.

A data run for a test body consisted of ten readings at each variation of its position from the free surface or rigid bottom, varying only one of these distances during a given run. Calibration checks were performed before and after each run.

An initial "proof test" was performed using a cylinder with end plates as the test body, and an added-mass coefficient of 0.988 was obtained, as compared to its theoretical value of 1.0.

The major source of experimental error resulted from the variation of period of vibration at a data point. For this reason, the average of ten readings taken at each data point was used to calculate the added mass. The root-mean-square

deviation from the average of the ten readings taken at any given data point was found to be $\leq$ 0.02 milliseconds. This deviation results in an error $\leq \pm 0.5$ gram in the determination of total weight from the calibration curves. Since the added-mass coefficient was calculated using added weight ($W_a = W_t - W$), this factor resulted in a deviation $\leq$ 0.006 in the added-mass coefficient. Errors in test body weights and displaced weights were negligible in comparison, being accurate within ± 0.05 gram.

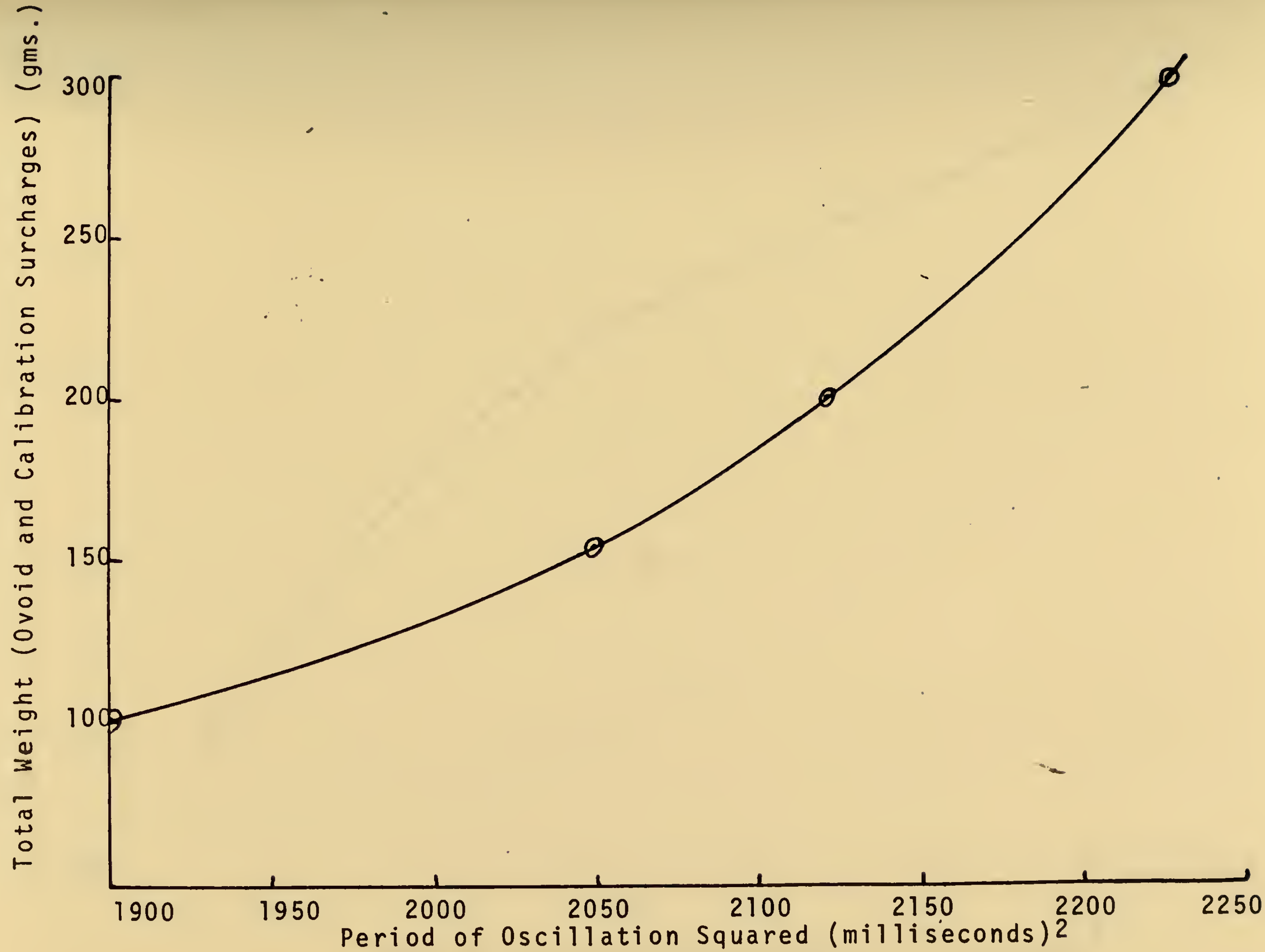


Fig. 7. CALIBRATION CURVE USED FOR THE RANKINE OVOID HAVING L/D = 7.65

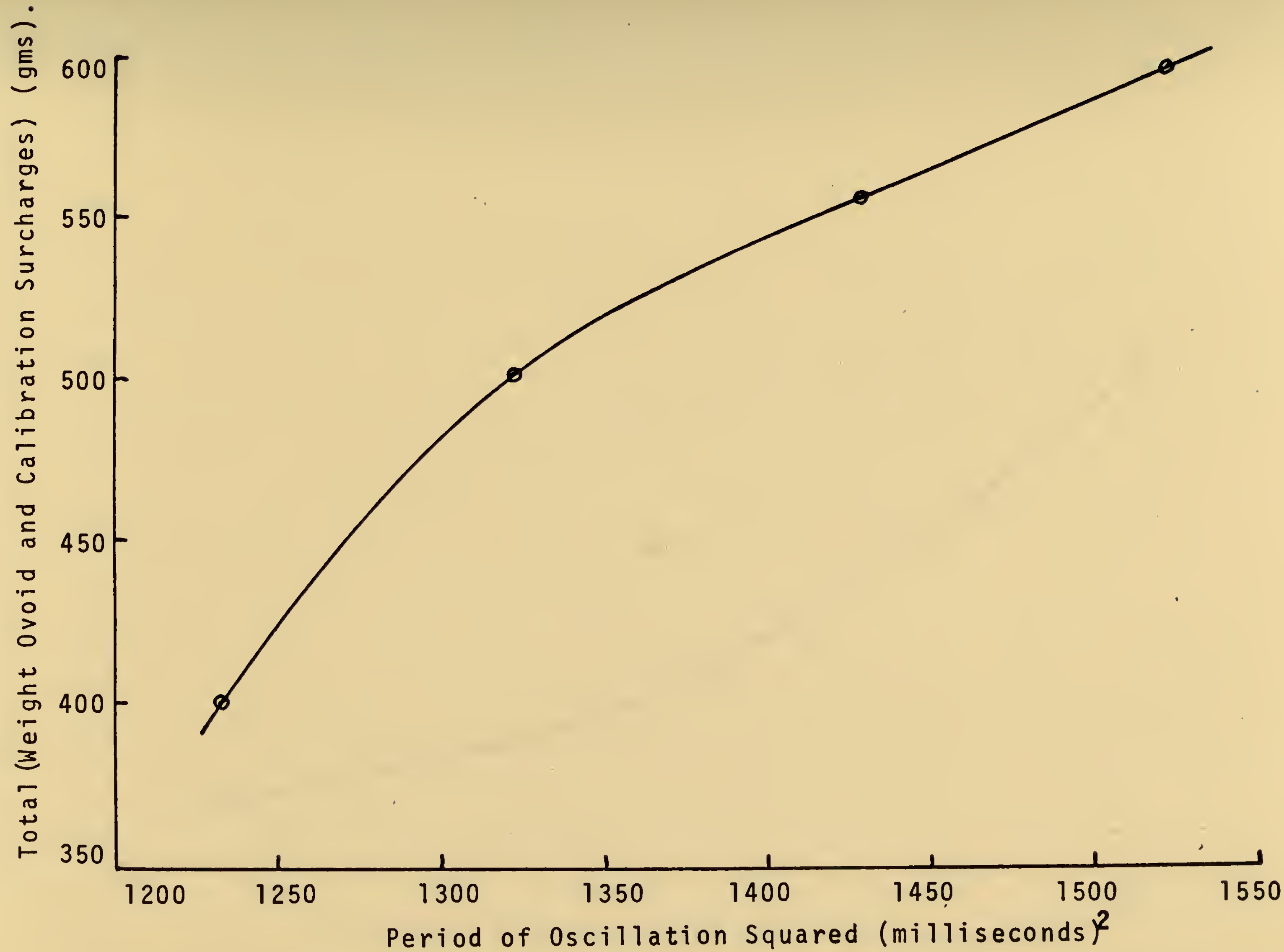


Fig. 8. CALIBRATION CURVE USED FOR THE RANKINE OVOID HAVING L/D = 6.4

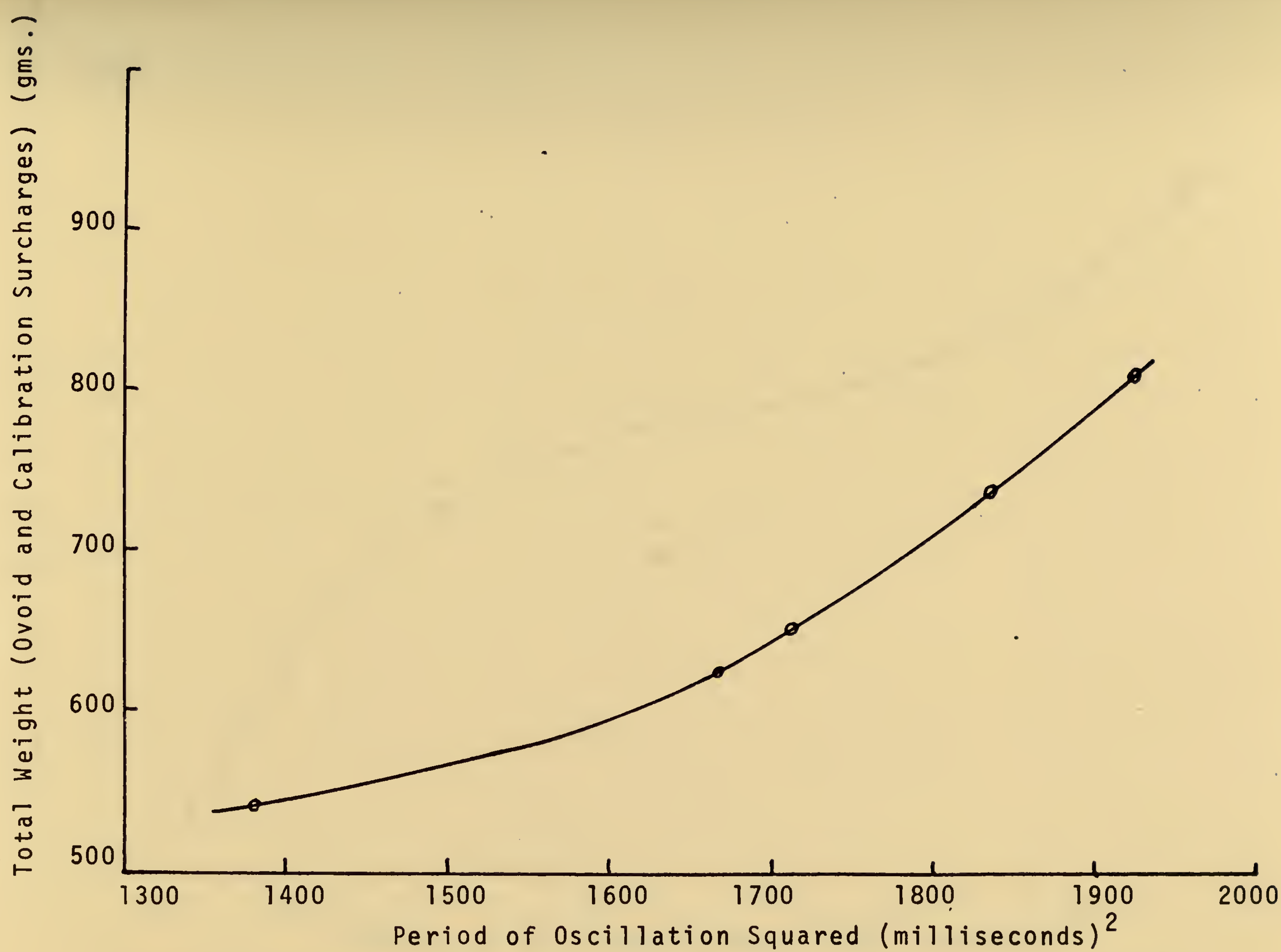


Fig. 9. CALIBRATION CURVE USED FOR THE RANKINE OVOID HAVING L/D = 5.33

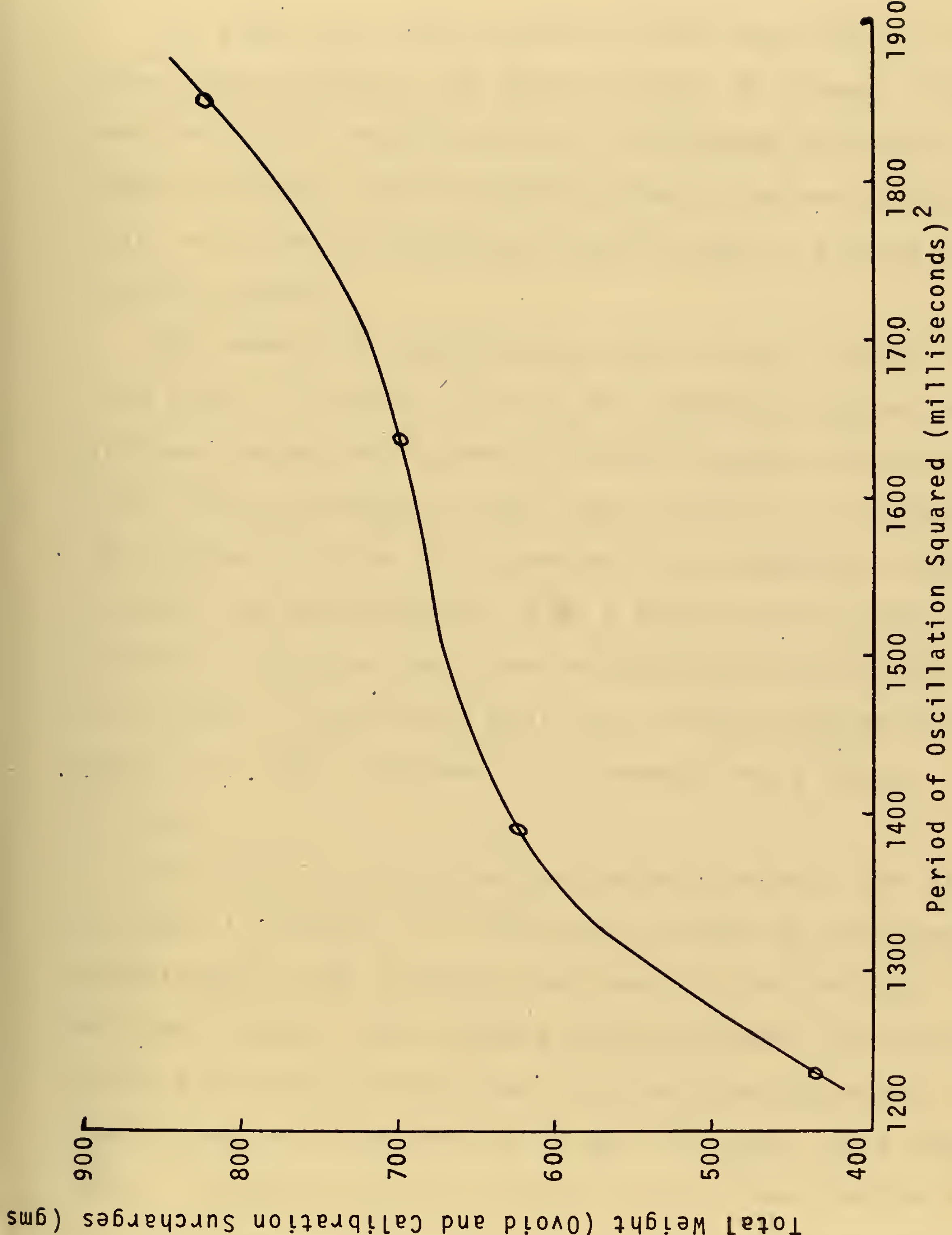


Fig. 10. CALIBRATION CURVE FOR THE RANKINE OVOID HAVING L/D = 4.0

IV. DISCUSSION OF RESULTS

The added-mass coefficients for each test body, as determined experimentally, are shown in Figs. 11 through 14 as a function of the free-surface or rigid-bottom proximity. Figure 15 shows the relationship between the body shape (L/D ratio) and the added-mass coefficient in a fluid of infinite extent.

The added-mass coefficients shown in Fig. 15 were obtained from Figs. 11 through 14, using the apparent constant value attained beyond the distance at which the free surface or rigid bottom appeared to exert very little or no influence. The increase in C as L/D increases is as expected, since a cylinder may be considered to be a Rankine ovoid with an infinite L/D ratio, and since the added-mass coefficient for a cylinder is larger than that for a finite axisymmetric body (e.g., for a cylinder C = 1 whereas for a sphere C = 0.5).

The free-surface and bottom-proximity effects are shown in Figs. 11 through 14. The rate of change of the added-mass coefficient as the proximity decreases is not the same for all test bodies. The distance at which either the free surface or rigid bottom ceased to affect the added-mass coefficient is in proportion to the L/D ratio. This dependency indicates that the influence of the free surface or rigid bottom is exerted at a greater distance for bodies of

larger L/D ratios. The effect of the free-surface proximity on the added-mass coefficient is more evenly distributed over the influence distance than the effect of the rigid-bottom proximity.

The added-mass coefficients determined for test bodies 1, 2, and 3 were independent of L/D for $\xi \leq 1$, varying by less than 4% in this region. This same consistency was obtained for test bodies 2, 3, and 4 within the same proximity to the free surface.

The effect of the free surface or bottom proximity on the added mass of a Rankine ovoid may be calculated through the use of distributed sources or the finite element method. The former method requires the determination of the appropriate source-strength distribution over the body in such a manner that the boundary conditions are satisfied both on the body (zero normal velocity) and the bottom (zero normal velocity) and/or at the free surface ($\frac{\partial^2 \phi}{\partial t^2} + g\frac{\partial \phi}{\partial y} = 0$) [1]. As far as the free surface condition is concerned, for low values of the Froude number F ($F = V/\sqrt{gD}$ where V is a characteristic velocity), the second term in

$$\frac{\partial^2 \phi}{\partial t^2} + g\frac{\partial \phi}{\partial y} = 0$$

is negligible and the flow behaves as though the interface were rigid so that ϕ satisfies a second boundary-value problem. At the other extreme, the first term is negligible and the surface condition corresponds to $\phi=0$. In terms of the image method, the low Froude number case involves the normal kind

of images (positive), whereas the high Froude number case involves inverse images. In the transitional regime the situation is more complex and is frequency dependent.

In the present study, an exact analysis of the dependency of the added mass of the Rankine ovoids on the bottom or free-surface proximity has not been attempted. Instead, an approximate calculation based on the strip method has been carried out. The strip method consists of the division of an axisymmetric body into small axisymmetric cylinders, evaluation of the added mass of each disk-like segment through the use of the added-mass coefficients obtained for a circular cylinder of corresponding position relative to the bottom or free surface, and summing the coefficients for all the elements. Obviously, this procedure ignores the effect of the three-dimensionality of the body. Furthermore, the added-mass coefficients so obtained approach unity for the infinite fluid case rather than those appropriate for a Rankine ovoid. Be that as it may, the strip method provides a quick estimation of the variation of the added-mass coefficient with distance to the wall or the free surface.

In the present calculation, the results of the analysis carried out for a circular cylinder by Müller [8] and Yamamoto, _et al_ [9] through the use of doublets and the image method were used. Figures 16 and 17 show the variation of the added-mass coefficient for a circular cylinder as a function of distance from the wall and the free surface (only the high

Froude number or $\phi = 0$ case) respectively. Evidently, Fig. 16 also represents the effect of the free-surface proximity for the low Froude number or $\frac{\partial \phi}{\partial y} = 0$ case.

The added-mass coefficients calculated through the use of Figs. 16 and 17 and the strip method are shown on Figs. 11 through 14. It is apparent from a comparison of the calculated results with those obtained experimentally that the strip method yields fairly accurate results, particularly for bodies close to a rigid plane wall. As expected, the calculations become increasingly more accurate as L/D increases and the proximity to the wall decreases. As noted previously, the limiting values corresponding to the infinite fluid case differ significantly because of the role played by the three-dimensionality of the body. In other words, in the close vicinity of a wall, the wall-proximity effect outweighs the three-dimensionality effect.

The added-mass coefficients calculated through the use of the strip method for the free surface case (both for $\phi = 0$ and $\frac{\partial \phi}{\partial y}=0$ conditions) are not as satisfactory as those calculated for the rigid wall case. Be that as it may, a careful examination of the experimental data and the calculated results shows that one could predict with a sufficient degree of accuracy the effect of both the wall and free-surface proximity if one were to shift the calculated curves downward so that their asymptotic values coincided with those obtained experimentally. This procedure is rather appealing considering

the fact that the added-mass coefficients for Rankine bodies immersed in an infinite fluid may be calculated (see Table I) thus providing the the asymptotic values to be used for the procedure suggested above. Finally, it should be noted that the added-mass coefficients discussed above are not the same for the Rankine ovoids moving against the wall (or the free surface) or parallel to it. This is true only for a circular cylinder.

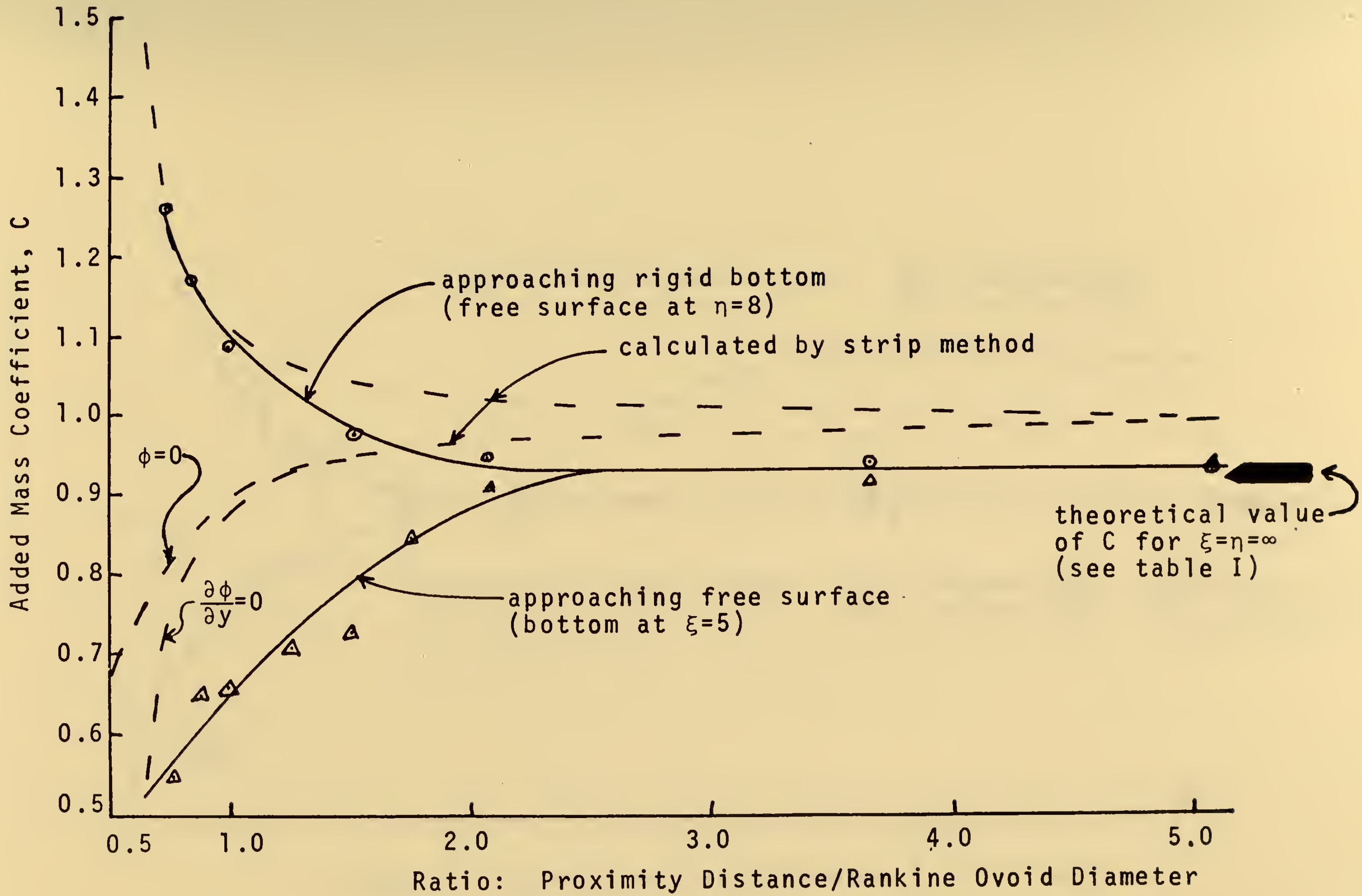


Fig. 11. ADDED MASS COEFFICIENT FOR THE RANKINE OVOID WITH L/D = 7.65

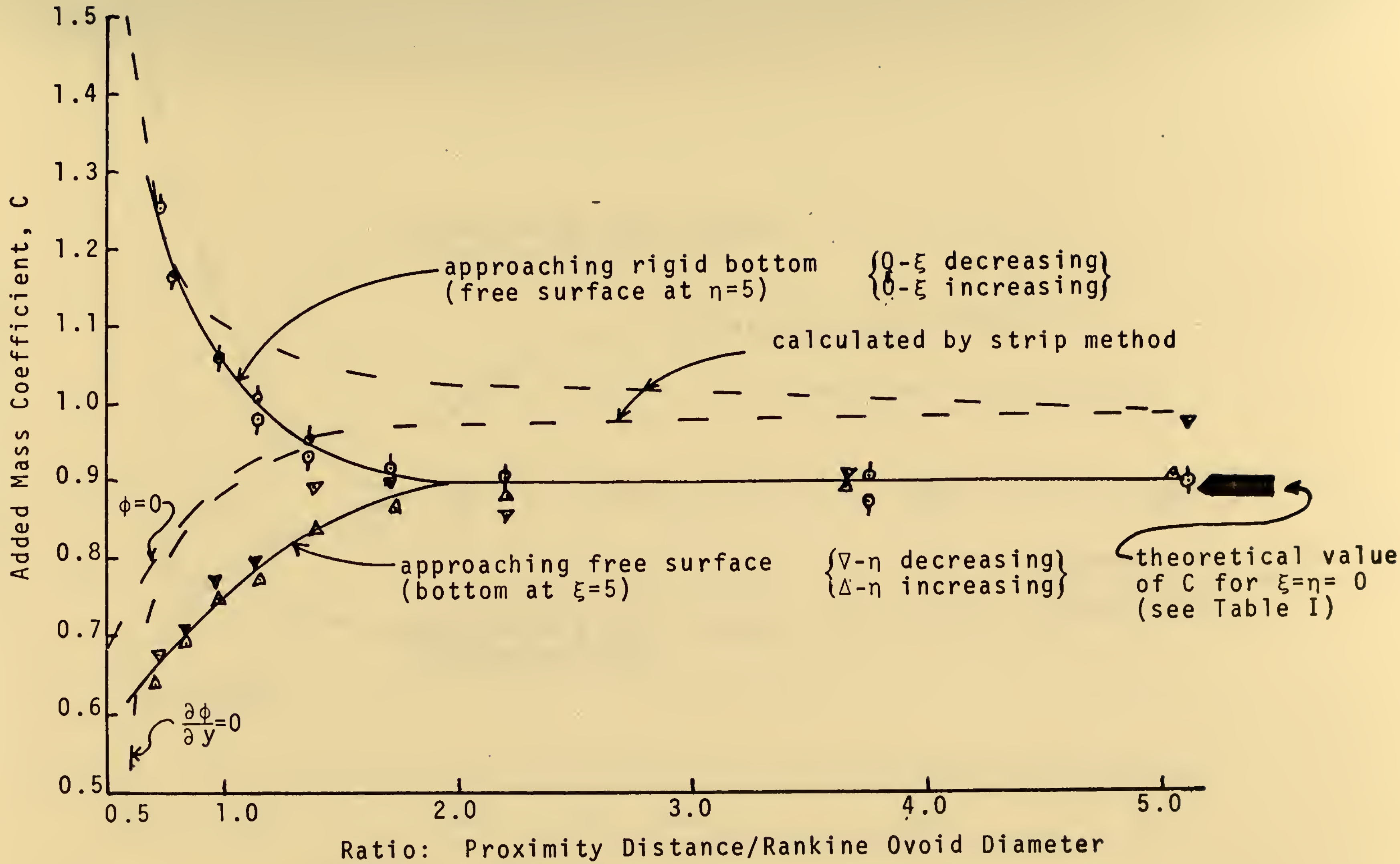


Fig. 12. ADDED MASS COEFFICIENT FOR THE RANKINE OVOID WITH L/D = 6.4

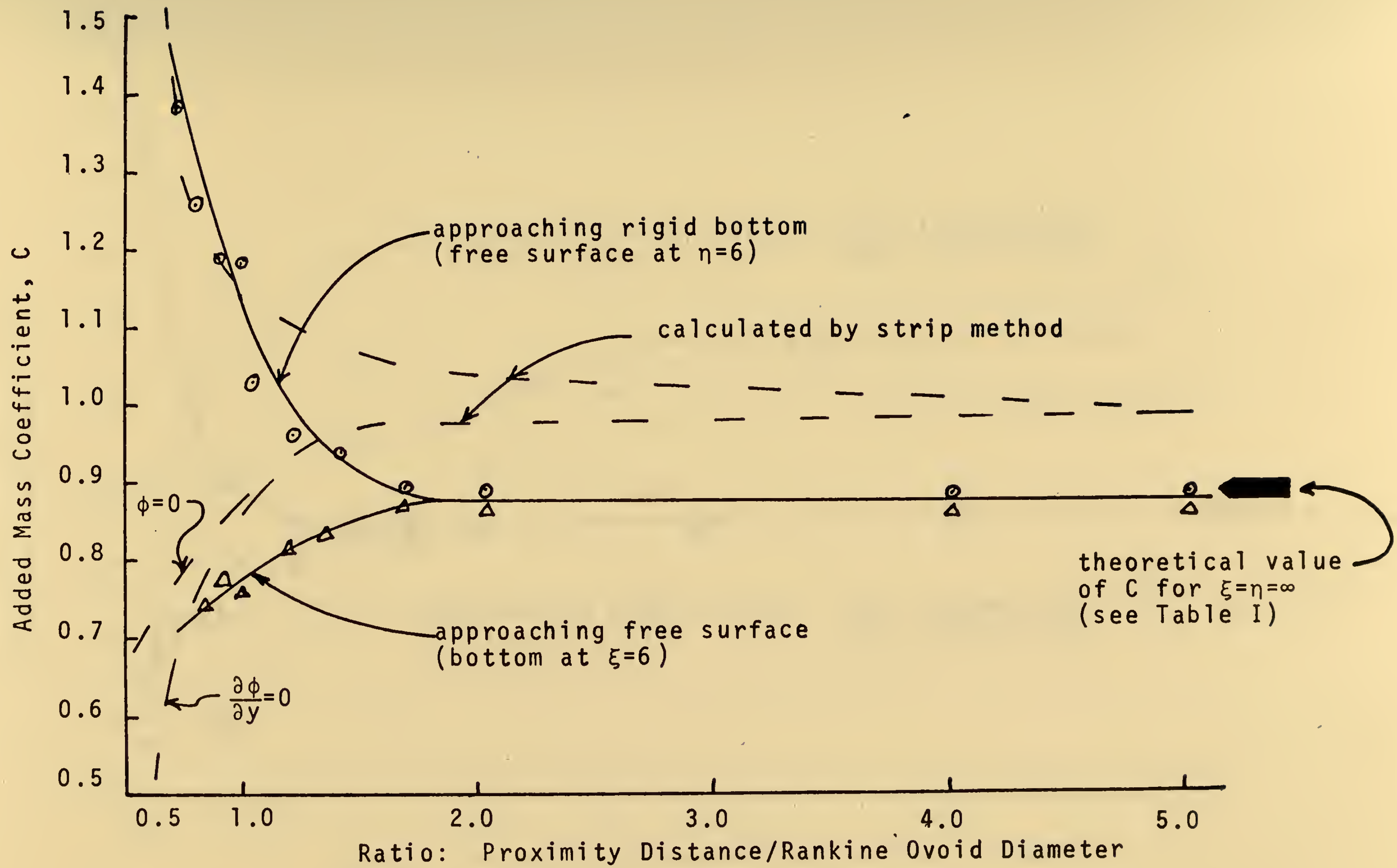


Fig. 13. ADDED MASS COEFFICIENT FOR THE RANKINE OVOID WITH L/D = 5.33

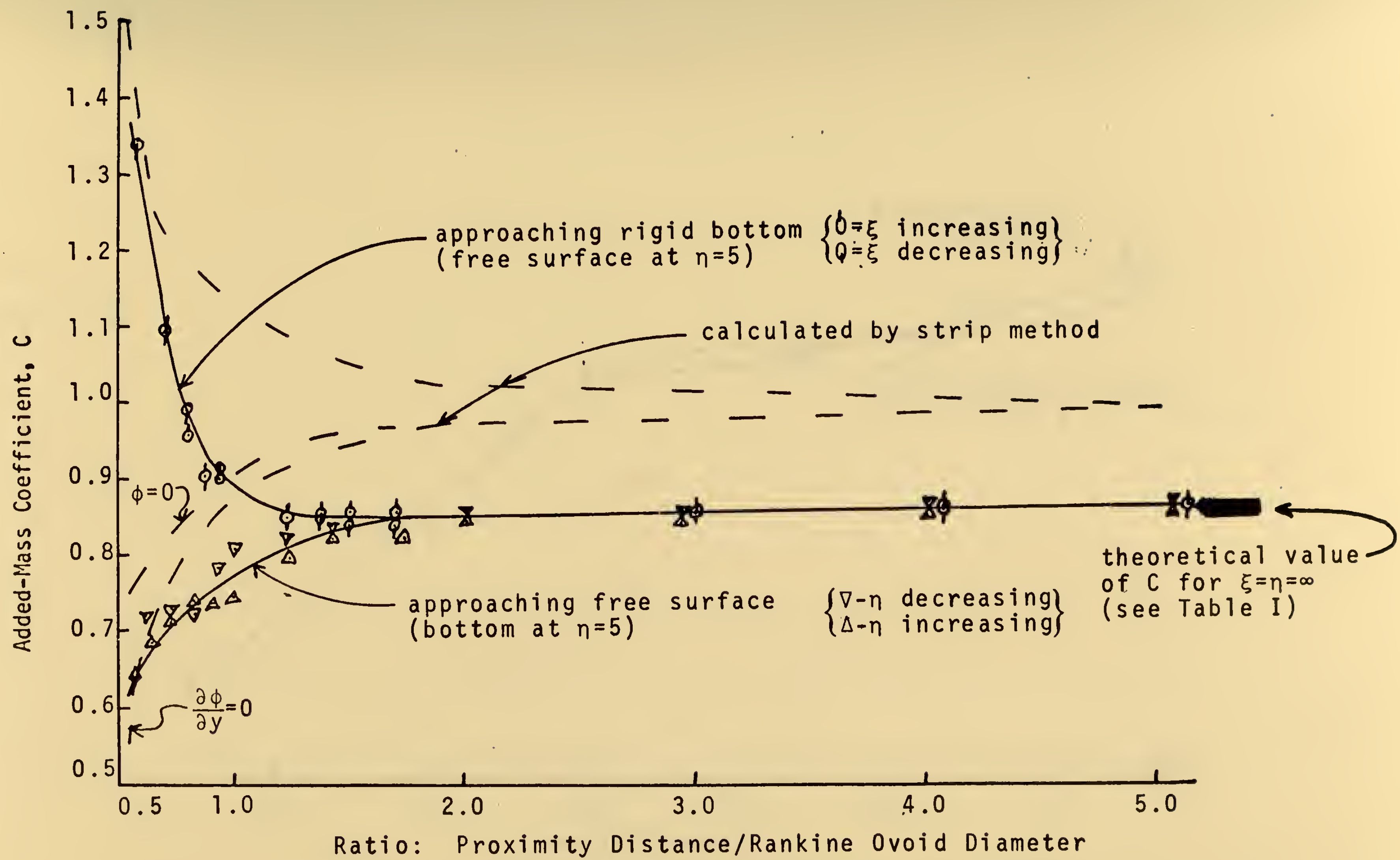


Fig. 14. ADDED MASS COEFFICIENT FOR THE RANKINE OVOID WITH L/D = 4.0

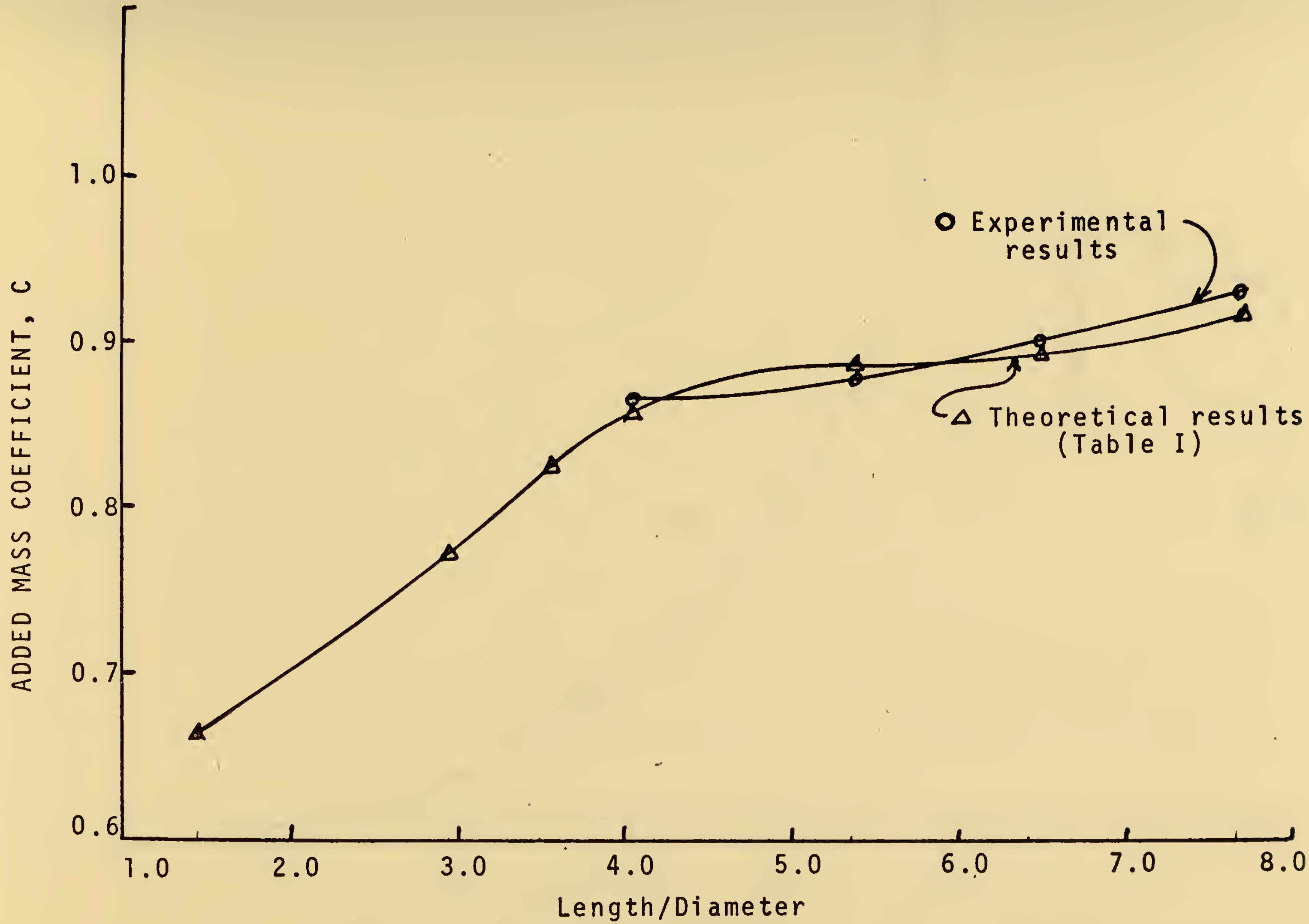


Fig. 15. ADDED MASS COEFFICIENTS FOR RANKINE OVOIDS IN AN INFINITE FLUID

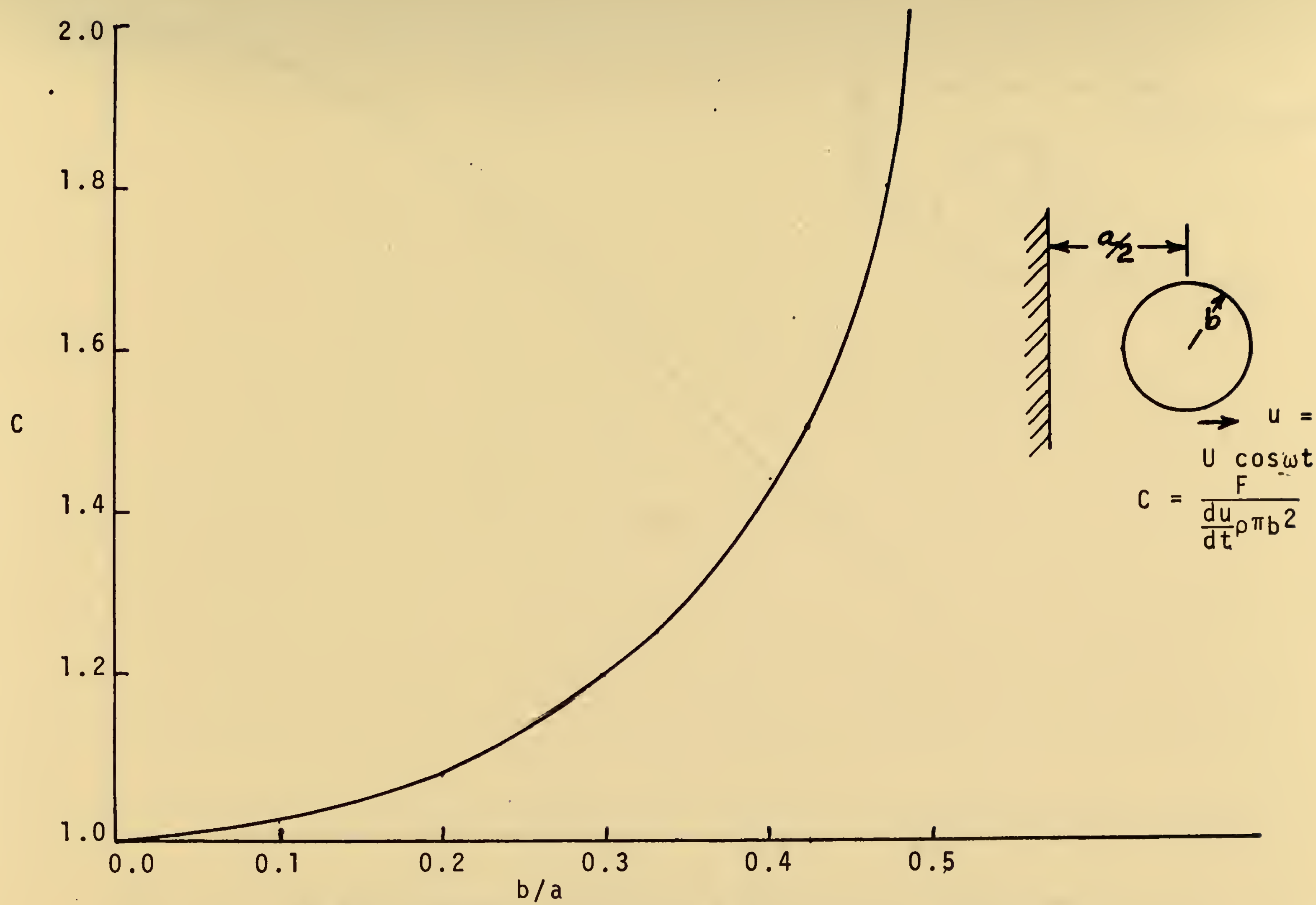


Fig. 16. THE WALL-PROXIMITY EFFECT ON THE ADDED MASS OF A CIRCULAR CYLINDER

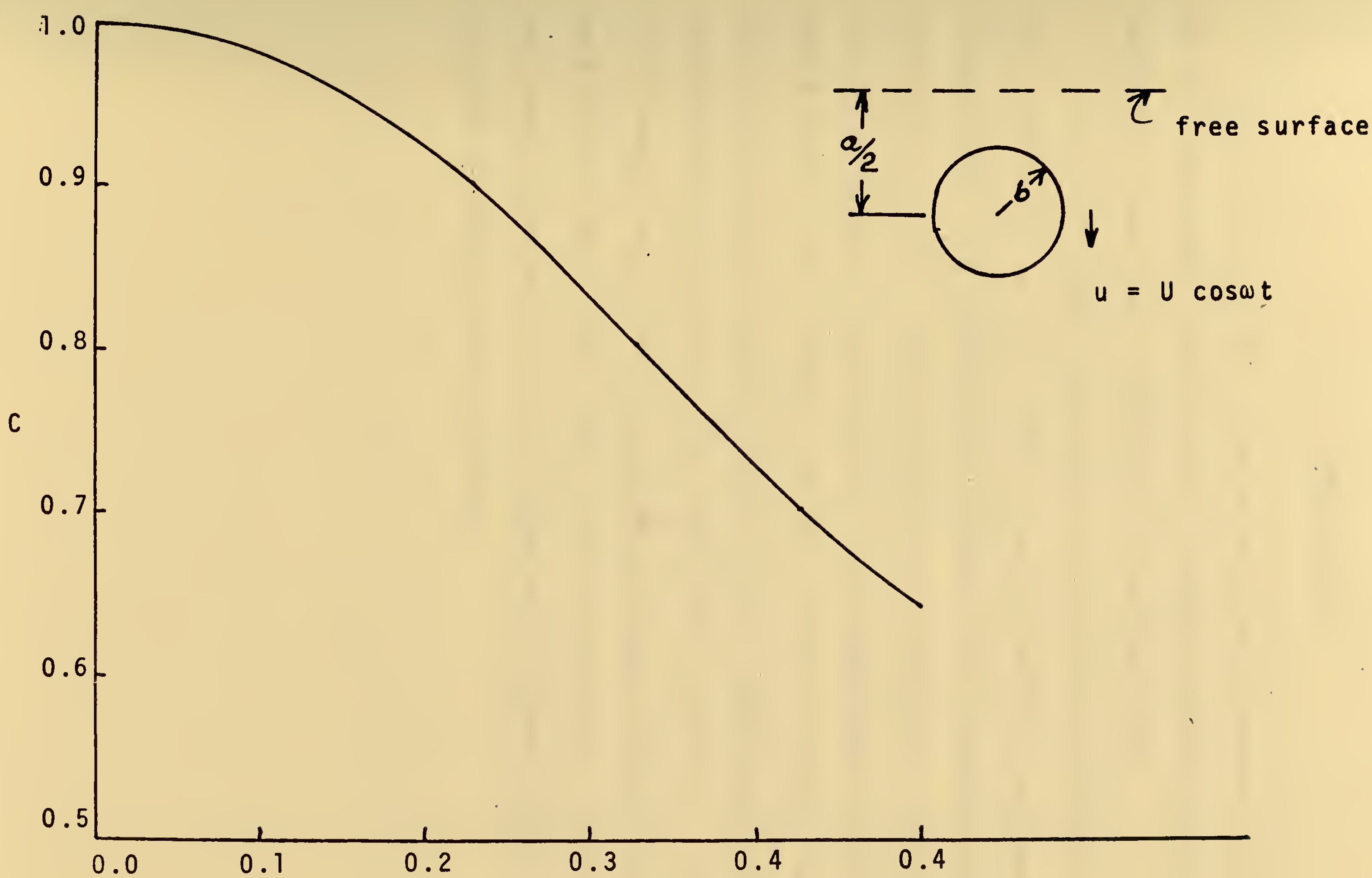


Fig. 17. THE FREE-SURFACE PROXIMITY EFFECT ON THE ADDED MASS OF A CIRCULAR CYLINDER

V. CONCLUSIONS

The effects of the free-surface and plane-wall proximity on the added-mass coefficient of Rankine ovoids oscillating vertically have been determined experimentally.

The results have shown that the bottom proximity increases the added mass and the free-surface proximity decreases it. Furthermore, the added mass increases with increasing length-to-diameter ratio and approaches that predicted analytically for an infinitely long cylinder. An approximate analysis based on the strip method and the cylinder results has shown that the bottom-proximity effect on the added mass of Rankine ovoids may be predicted with sufficient accuracy. Finally, it is noted that both the bottom and free-surface effects may be predicted to a first order of approximation by matching the asymptotic values of the added-mass coefficients for the cylinder and the Rankine ovoids.

LIST OF REFERENCES

1. Robertson, J. M., Hydrodynamics in Theory and Application, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1965.

2. Morrison, J. R., et al, "The Force Exerted by Surface Waves on Piles," Transactions, AIME, Vol. 189, 1950.

3. Waugh, J. G., and Ellis, A. T., "Fluid Free Surface Proximity Effect on a Sphere Vertically Accelerated from Rest," J. Hydronautics, Vol. 3, No. 4, Oct. 1969.

4. Sarpkaya, T., "Added Mass of Lenses and Parallel Plates," J. Engineering Mechanics Division Proceedings, ASCE, Vol. 86, No. EM3, June 1960.

5. Garrison, C. J., "Added Mass of a Circular Cylinder in Contact with a Rigid Boundary," J. Hydronautics, Vol. 6, No. 1, Jan. 1972.

6. Garrison, C. J., and Berklite, R. B., "Impulsive Hydrodynamics of Submerged Rigid Bodies," J. Engineering Mechanics Division, Proceedings, ASCE, Vol. 99, No. EM1, Feb. 1973.

7. Rosenhead, L., ed., Laminar Boundary Layers, Oxford University Press, Oxford, 1963.

8. Müller, von Wilhelm, "Systeme von Doppelquellen in der ebenen Strömung, insbesondere die Strömung um zwei Kreiszylinder," Ztschr, für Angew. Math. und Mech., Bund 9, Helf 3, pp 200-213, Juni 1929.

9. Yamamoto, T., Nath, J., and Slotta, L., "Yet Another Report on Cylinder Drag or Wave Force on Horizontal Submerged Cylinders," Oregon State University Bulletin No. 47, April 1973, Corvalis, Oregon.

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The free-surface and bottom-proximity effects on the added mass of Rankine ovoids of various length-to-diameter ratios were experimentally investigated by vectically oscillating the ovoids normal to their major axis.

The results have shown that the bottom-proximity increases the added mass and the free-surface proximity decreases it.

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Furthermore, the added mass increases with increasing length-to-diameter ratio, i.e., for more cylinder-like ovoids, and approaches that predicted analytically for an infinitely long cylinder. Finally, an appropriate analysis based on the strip-method and the cylinder results has shown that the bottom-proximity effect on the added mass of Rankine ovoids may be predicted with sufficient accuracy. The prediction of the surface-proximity effect requires more refined methods.

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